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STRUCTURAL VIBRATIONS PRODUCED BY GROUND MOTION

D. E. Hudson[1] and G. W. Housner,[a] A.M., ASCE

SUMMARY

Simultaneous measurements of transient ground motion and of the resulting structural vibrations in a steel frame building caused by a large quarry blast are described. Building accelerations computed from the measured ground accelerations are compared directly with measurements made in the building. The satisfactory agreement between the calculated and measured building response indicates that the general method of replacing a complex structure by a simplified dynamic model gives results of engineering significance even for complicated transient loadings.

INTRODUCTION

The desire for a continual improvement in the strength-weight efficiency of structures of all kinds has led to an increased study of the effects of various dynamic loads on buildings. Among the loads which have been extensively investigated are those caused by earthquakes, by both air-borne and earth-borne explosive shocks, and by self-excited oscillations maintained by the wind. For a satisfactory analysis of such problems it must be possible to compute, with the required accuracy, the motions that would be caused by various loadings. While considerable difficulty has been experienced in the past in making theory and observation agree in this field, the work described in the present paper shows that a satisfactory agreement can be obtained when all of the factors entering into the problem are properly accounted for. Although the present investigation is concerned specifically with the transient loads caused by an explosive-generated ground shock, the methods of computation are equally applicable to any kind of dynamic loading problem. It will perhaps be worthwhile, therefore, to give first a brief account of the methods used for such transient dynamic problems, and then to present the test results which will illustrate the applicability of the theory.

As a first step in the computation of the deflections or motions of any actual structure, it will always be necessary to make simplifying assumptions to reduce the complexity of the structure to the point where calculations are practicable. For statics problems, many of the necessary simplifying assumptions have been so sanctioned by past experience that the designer is hardly conscious that they are in fact assumptions. For dynamics problems, however, the additional complexity of the theory, and the lack of a sufficiently large body of experience and of test results, has introduced an increased uncertainty as to just what simplifying assumptions are really justified. Perhaps the most fundamental problem involved in any theoretical design work is

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is the question of how far these simplifying assumptions can be carried without losing some features of engineering significance.

The Dynamic Model of a Structure

The three characteristics of any structure which determine its behavior under dynamic loads are the masses of the various elements, the stiffnesses of the members, and the energy dissipations which arise from such factors as friction in joints. The simplest dynamic model of a structure would be one in which each of these basic characteristics appeared in its simplest form. This simplest possible system, which will hereafter be referred to as the "simple system", is illustrated in Fig. 1a, where all of the mass of the structure, m, is concentrated at one point, all of the stiffness of the system is represented by one massless linear spring of spring constant k, and all of the energy dissipating mechanisms in the structure are concentrated in one damping element described by some dissipation factor c.

Actual structures will often have to be represented by somewhat more complicated dynamic models. If, for example, the horizontal motions of the three-story building shown in Fig. 1b were to be investigated, the dynamic model of Fig. 1c might be set up, where 3 masses, 3 springs, and 5 damping elements are used. A very important feature of these more complex models is that they can always be replaced by a number of simple systems. Thus the behavior of the complex system of Fig. 1c can be computed by a superposition of the behavior of the three simple systems of Fig. 1d.

Because of the great simplicity of the simple system compared to the actual structures of interest to the engineer, there has been a tendency for some engineers to doubt the value of work based on such a model. It is worthwhile emphasizing, therefore, that the importance of the simple system as a dynamic model is based on two considerations:

1. In spite of its simplicity, the model does preserve the major features of many engineering structures, so that it gives a direct picture of their behavior for many dynamic loads.
2. More complex structures can always be considered as equivalent to a series of simple systems, and the behavior of the complex structure can be obtained by adding the effects of the individual simple systems. The simple system can thus be considered as a "building block" for the more complex systems.

The Experimental Program

Because of the difficulty of generating large transient forces suitable for test purposes, there have been relatively few direct experiments on the effects of dynamic loads on actual structures. In connection with earthquake studies there have been many steady state vibration tests aimed at finding the resonant periods of buildings. These tests have usually been carried out at very low stress levels, not only because of the force limitations of the available mechanical oscillators, but also because of the danger of damage to the structure.

In the future valuable data may be expected from the earthquake strong motion accelerometer program of the United States Coast and Geodetic Survey. The data obtained under this program so far have been almost entirely in the form of ground acceleration records. There are at present several accelerometer installations in buildings, but there has been as yet no

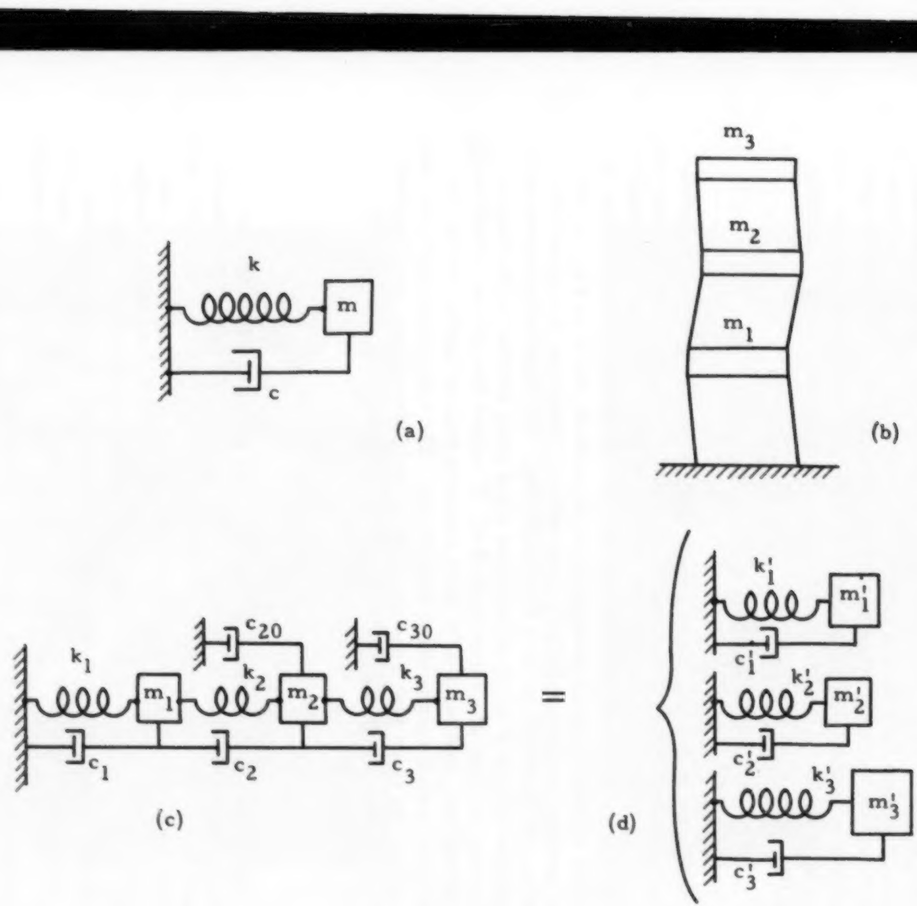

FIG. 1. THE DYNAMIC MODEL OF A STRUCTURE

simultaneous measurement of both ground and building motions for earthquakes of a magnitude sufficient to cause significant structural loadings.

Quarry blasts are another possible source of test data. Most of these blasts, however, are small in size, and are not located close enough to typical building structures to give usable results. In view of these difficulties, it was fortunate that the Minnesota Mining and Manufacturing Company planned to detonate a large quarry blast sufficiently near a modern well designed and constructed building so that it would be subjected to a reasonably strong ground motion. The opportunity afforded by the company to make measurements during this blast thus made it possible for the first time to measure simultaneously relatively strong ground motion and the consequent motion of a typical building. It thus becomes possible to compare directly the measured building motion with the motions that would be calculated based on various simplified dynamic models, and hence to evaluate directly the practical value of the theoretical analysis.

Description of the Test Building

The photographs of Figs. 2 and 3 show the general features of the steel-frame mill building in which the measurements were made. The building consists of two sections which in many respects act independently. The lower portion of the building connects into the higher end at intermediate points in the vertical 10WF39 column members, as at points A and B in Fig. 4. Because of bending in these relatively long vertical members the connection between the two portions is not a very rigid one. The most important masses in the system are the 6 in. thick concrete floor slab, located in the higher portion of the building at an elevation of 45' 8" above the ground, which weighs about 180,000 lbs., and the 1-1/2' thick concrete wall at the far end of the lower section, which weighs about 350,000 lbs. The cross-bracing in the end frames below the floor slab consists of 4H10 welded sections, and the other cross braces shown schematically in Fig. 4 are either 1 in. or 1-1/2 in. diameter round bars.[(1)*]

The Instruments

The measuring instruments used for both the ground motion and the building motion were seismic type accelerometers. The particular instrument used had a variable-reluctance balanced-armature type of seismic element, with a natural frequency of approximately 80 cycles per second and fluid damping of about 60 % of critical.[(2)] The accelerometer signal modulated the output of a 2000 cycles per second alternating current bridge circuit, and this bridge circuit output was then amplified, demodulated, and finally recorded on paper by a direct pen-writing oscillograph. The overall frequency characteristics of the accelerometer-recorder system are essentially constant from zero to about 100 cycles per second.

In Fig. 5 the installation of this measuring and recording system at the upper floor slab position is shown. The recording oscillograph is at the right, and the larger instrument at its left contains the 2000 cycle per second oscillator, the amplifier, and the input bridge circuits. Connected to this amplifier unit at the left may be seen the small accelerometer, mounted on a right angle bracket to record horizontal accelerations of the floor slab. The

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*Numbers in parentheses refer to references at end of paper.

FIG. 2. GENERAL VIEW OF TEST BUILDING

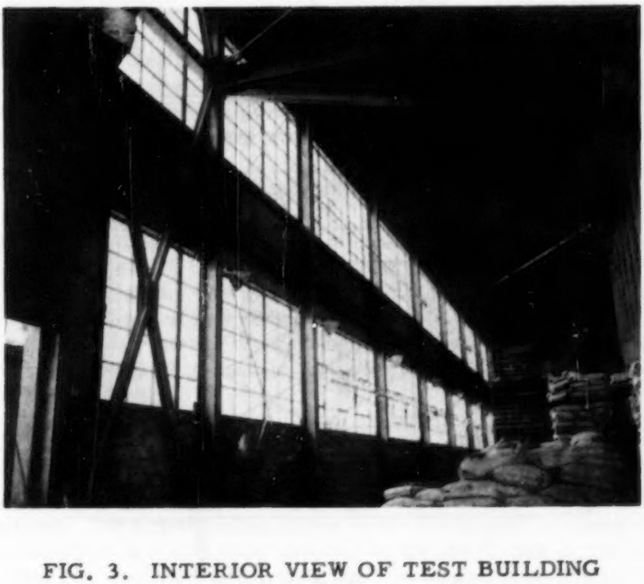


FIG. 3. INTERIOR VIEW OF TEST BUILDING

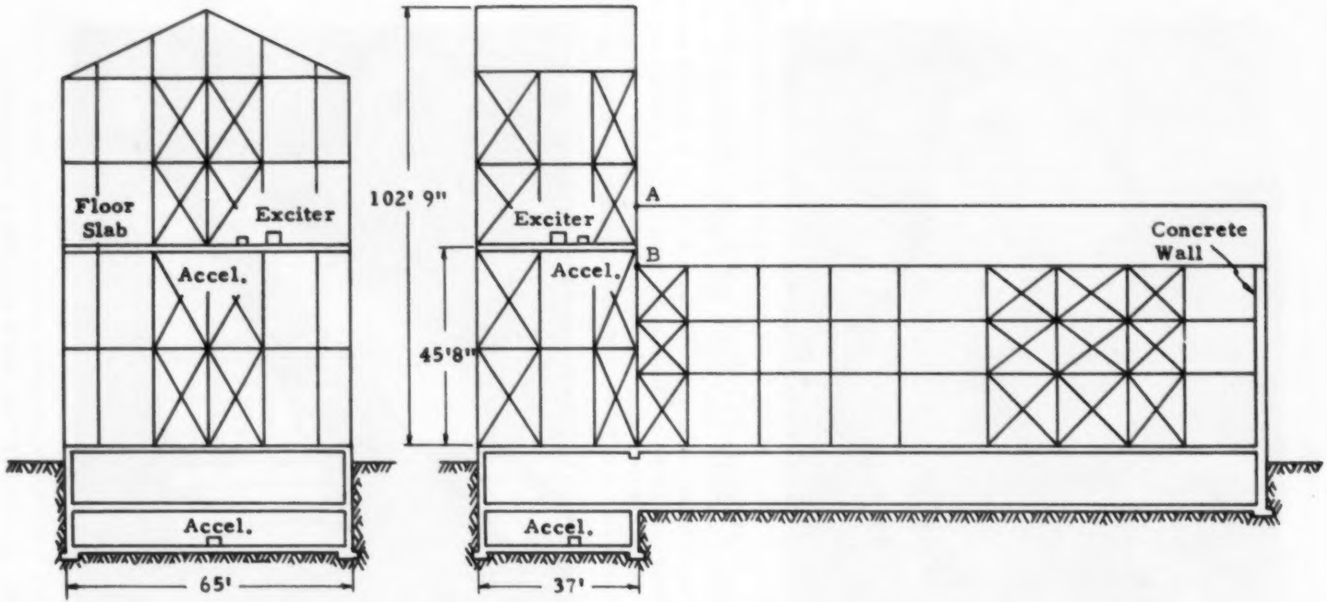


FIG. 4. SCHEMATIC DRAWING OF TEST BUILDING

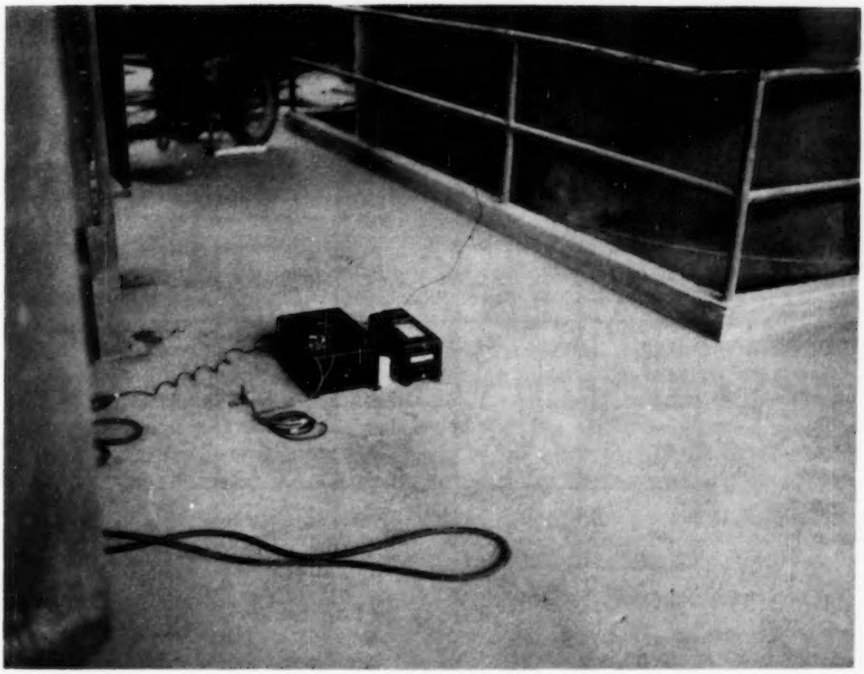


FIG. 5. INSTRUMENTATION SYSTEM IN POSITION

locations of the accelerometer and of the similar accelerometer and recording system in the sub-basement, are shown in Fig. 4. The accelerometers were oriented so that horizontal accelerations in the direction of the short side of the higher portion of the building would be measured.

The Explosive Charge

The explosive charge was detonated at a horizontal distance of about 370 yards from the tall end of the building, and 60 yards above the elevation of the building ground level. The 370,000 lb. charge of Nitromon explosive was packed in several hundred feet of tunnel cut into the sloping side of the mountain.(1) In Fig. 2, that part of the sloping mountain side behind the top of the tall telephone pole just at the left of the building is the approximate location of the explosive charge.

The Recorded Ground Motion

In Fig. 6 is shown the measured ground motion as plotted from the oscillograph record. The acceleration shown is the horizontal component of the ground acceleration in a direction parallel to the short side of the tall portion of the building. It is of interest to note that the magnitudes attained are equal to those of a moderately strong earthquake, and that the general periods and

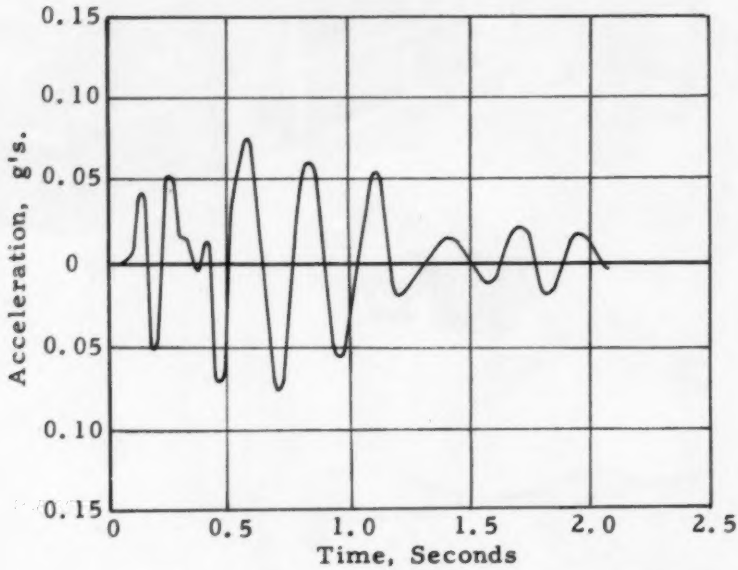


FIG. 6. MEASURED GROUND MOTION

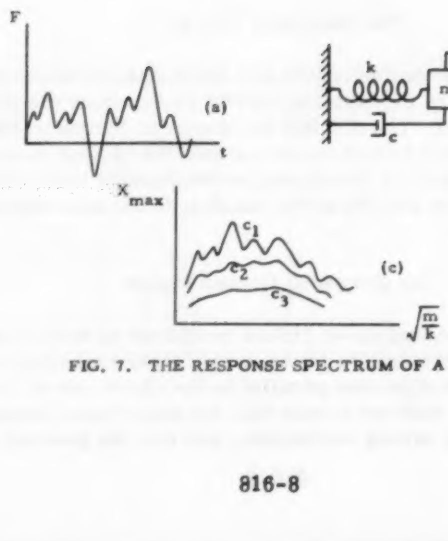


FIG. 7. THE RESPONSE SPECTRUM OF A FORCE

wave form are very similar to the initial portion of a typical earthquake. The ground accelerations of some recorded strong earthquakes have been two to three times as large as those of Fig. 6, and the motions have lasted from fifteen to twenty times as long.

The Response Spectrum of the Ground Motion

Having the experimentally determined ground motion and hence the exciting forces acting on the building, consequent behavior of the building can be calculated. As discussed above in the introduction, the method will be to replace the actual building structure by several equivalent simple systems. The first problem, therefore, will be to compute the behavior of a simple spring-mass system under the action of the recorded ground motion.

It has been found that a convenient way of describing the behavior of the simple system is by means of the so-called "response spectrum." Suppose that a force F is given which varies with time in some known way, as shown in Fig. 7a. A quantity is then chosen to define the motion of the simple system, such as the displacement X, shown in Fig. 7b. To show in one set of curves the behavior of the system of Fig. 7b for all values of the basic characteristics m, k, and c, the maximum value of the displacement X_{max} versus the quantity $\sqrt{\frac{m}{k}}$, for various values of c, is plotted. Such a set of curves, shown in Fig. 7c, is called the response spectrum of the force F. Since the quantity $\sqrt{\frac{m}{k}}$ is just the natural period of vibration of the simple system for c = 0, or the reciprocal of the natural frequency, such response spectrum curves are often called "frequency response curves."

The concept of the response spectrum shifts the emphasis in a dynamics problem from the applied force to the behavior of the system under the action of the force, and thus the response spectrum deals directly with the aspect of the problem of most concern to the engineer. For most problems the engineer would be better off knowing the response spectrum than knowing the force itself. Consequently there has been a considerable amount of work, particularly in the field of engineering seismology, in obtaining typical response spectra.

There are other measures of the behavior of a system which can also be plotted in the form of a response spectrum. For example, in Fig. 7b, the relative displacement between the mass and the support, i. e., the total strain in the spring, or the relative or absolute velocities or accelerations of the mass might be used as the response. The particular quantity selected will depend upon the nature of the problem being studied. By using the more general term "response" all of these possibilities are included under one concept.

The response spectrum will give a direct picture of the behavior of a structure to the extent that the structure can be represented by the one degree of freedom simple system. The total response of a complex system can be approximately determined from the response spectrum by superposition. This superposition is, however, not exact, because the response spectrum in its simple form does not retain any information as to the phase relationships between the motions in the various modes of vibration. The assumption that maximum responses in the various modes occur simultaneously may overestimate the total response for some systems. For many complex structures, however, this summation of the maximum responses will give results of

engineering accuracy, so that even for very complicated structures the response spectrum concept is of considerable utility.

For the present problem the acceleration response spectrum will be used, since acceleration is the quantity which is directly measured. The problem of determining the acceleration spectrum, given a complicated acceleration-time function as in the present problem, is itself a difficult one, and is best solved by the use of high-speed computer techniques. In the present case, the spectrum was obtained by the use of the Electric Analog Computer of the Analysis Laboratory at the California Institute of Technology.[3, 4] The spectrum obtained for the quarry blast ground acceleration is shown in Fig. 8.

The Dynamic Model of the Building

From the response spectrum of Fig. 8 the behavior of the building can be predicted if the building can be replaced by a dynamic model consisting of several simple systems. In Fig. 4 it can be observed that the two main m masses of the structure, the floor slab in the tall portion, and the vertical wall at the other end of the long section, are separated by structure of considerable flexibility, and hence the two masses would not be expected to behave in the same way. This means that the whole structure cannot be represented by just one concentrated mass, i. e., as one simple system, but that at least two masses and two springs must be retained in the model. As a tentative model for the structure the two-mass system shown in Fig. 9 is assumed. The mass m_1 includes the mass of the concrete floor slab, plus a fraction of the mass of the roof and walls. The mass m_2 includes a portion of the vertical concrete wall mass plus a fraction of the roof and sidewall mass. The fractions of the roof and wall masses used were computed on the basis of tributary loads resisted by the wall frames. The cantilever spring k_1 was the computed spring constant for one side frame which supports one-half of the concrete slab. This was determined by computing the static deflection caused by a given horizontal force applied at the floor slab. The cantilever spring k_2 was similarly computed for the side framing supporting the roof and the vertical wall of the long portion of building. The coupling spring k_3 was computed by considering the bending of the vertical members as at A and B in Fig. 4. These calculated values of masses and spring constants are of course subject to some variation depending upon the assumptions made as to mass distribution, joint rigidities, etc., but it is believed that they should be within 10% of the correct values and it will be seen from the later results that this accuracy is sufficient for the present purpose.

Given the two mass model of Fig. 9, the two natural periods can be computed.[5] The results for the numerical values of Fig. 9 are 0.278 seconds for the shorter period and 0.347 seconds for the longer period. The question of which of these two periods would be excited by the ground motion must now be considered. In Fig. 10, a still further simplification of the structure is introduced, in that in this model the masses and the cantilever spring constants are equal. The two kinds of motion possible in Fig. 10a are shown in Fig. 10b and c. In Fig. 10b, corresponding to the longer period, the two masses move in the same direction, whereas in Fig. 10c, corresponding to the shorter period, the masses always move in opposite directions. A very similar behavior would be expected from Fig. 9, since the masses and cantilever spring constants there are approximately equal.

It should next be noted that during the ground motion both masses are acted upon simultaneously by spring forces, and hence at the start of the motion

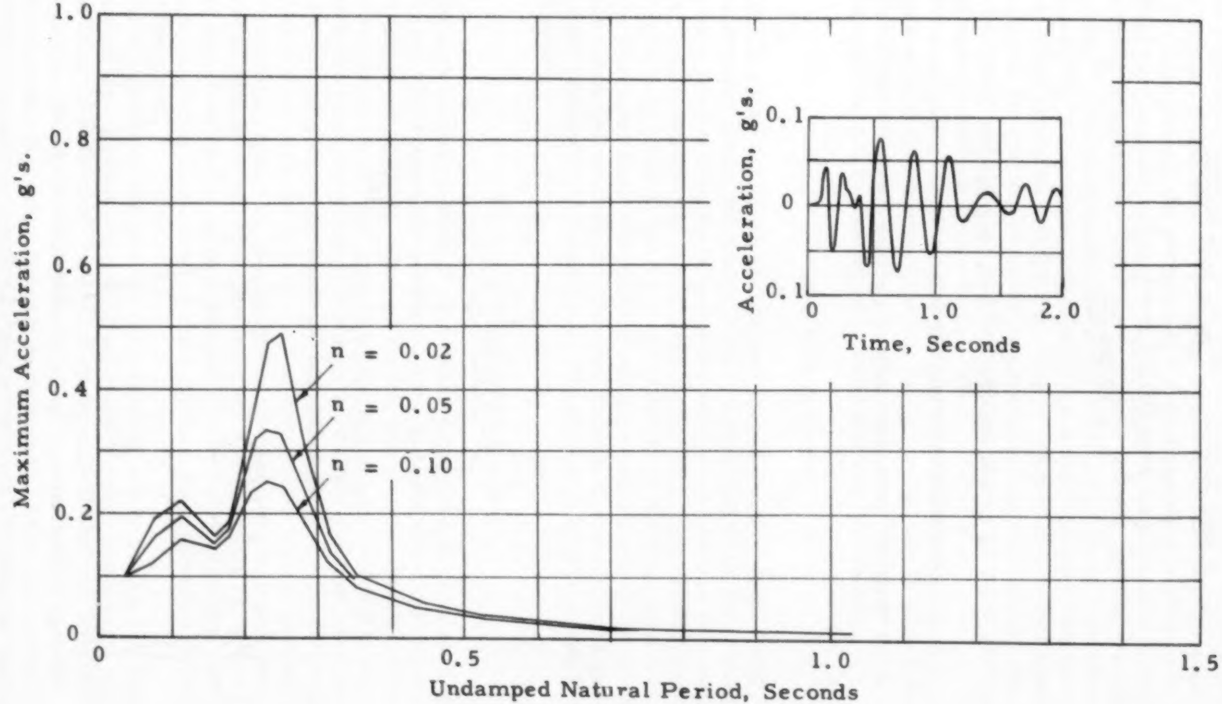


FIG. 8. QUARRY BLAST ACCELERATION RESPONSE SPECTRUM

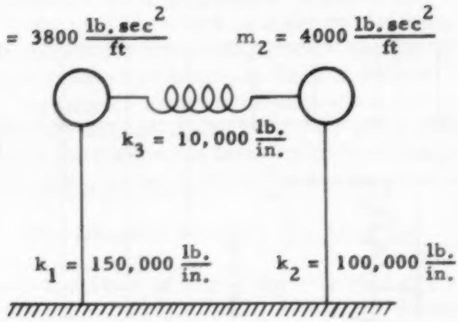


FIG. 9. DYNAMIC MODEL OF BUILDING

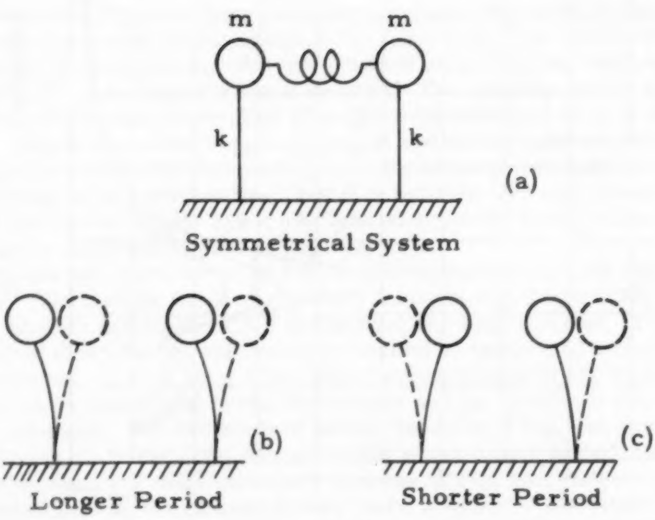


FIG. 10. SIMPLIFIED DYNAMIC MODEL OF BUILDING

both masses should move in the same direction. The ground motion would thus be expected to excite primarily the longer period. The magnitude of the acceleration which should correspond to this longer period could be determined from the spectrum curve of Fig. 8, if the damping in the structure were known. It can be seen from Fig. 8, however, that in the region of the 0.347 second period, the response is not particularly sensitive to damping, and hence a complete analysis of the damping in the structure is not necessary and an approximate value based on past tests of building structures can be taken.(6) Using a damping value of $n = 0.05$, it is found from the spectrum curves of Fig. 8 corresponding to a period of 0.347 second, that the peak acceleration should be about 0.1 g. It is of interest to note that similar calculations of the building response to several strong earthquakes that have been recorded show that the building motions caused by those earthquakes would have been much larger than 0.1 g.

The conclusion, then, based on the analysis of the ground acceleration and the dynamics of the structure, is that the floor slab should show a dominant period of approximately 0.347 sec. and a peak acceleration of 0.1 g. This calculation can now be compared directly with the test results.

The Test Results

Fig. 11 shows the acceleration-time record obtained from the floor slab accelerometer during the blast. It will be seen that while there is evidence of at least two periods, there is a dominant period, and that its magnitude checks satisfactorily with the calculated one. The peak acceleration is also seen to be very close to the 0.1 g calculated from the blast spectrum. It may thus be concluded from this satisfactory agreement between the calculated and the measured motions that the main factors of engineering significance have been retained in the model even though many simplifications have been introduced.

Vibration Tests of the Building

Although for the building of the present tests the natural periods could be calculated with reasonable accuracy, it would be expected that for some applications more accurate values of the periods than can readily be computed might be required. These more accurate values would probably best be obtained by a direct steady-state vibration test of the building. Such a vibration test would also give values of structural damping. While the structural damping did not turn out to be of critical importance for the present test, this was to a certain extent fortuitous, and in general damping would be expected to have an important effect on the response of a structure to dynamic loads. It was thus decided that as an additional check, and to provide a direct comparison of transient and steady-state response, vibration tests of the building should be made.

The vibration exciter used as the source of an alternating sinusoidal force was a counter-rotating unbalanced-mass machine borrowed from the United States Coast and Geodetic Survey. A photograph of this unit installed on the floor slab in the tall portion of the building is shown in Fig. 12. The unit produces a total horizontal force in pounds given by the expression $F = 12f^2$, where f is the frequency in cycles per second corresponding to the rotational speed of the exciter. The unit was driven by a thyratron-controlled variable speed D.C. motor which permitted a close adjustment of speed, and a smooth variation of speed through the resonant periods. The exciter was located

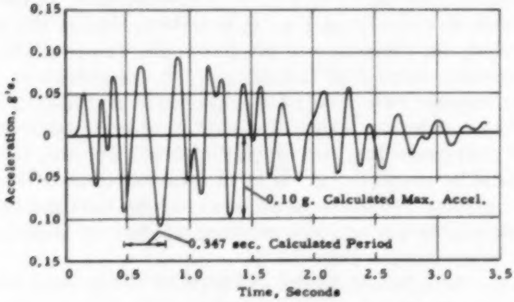


FIG. 11. ACCELERATION-TIME RECORD OF FLOOR SLAB

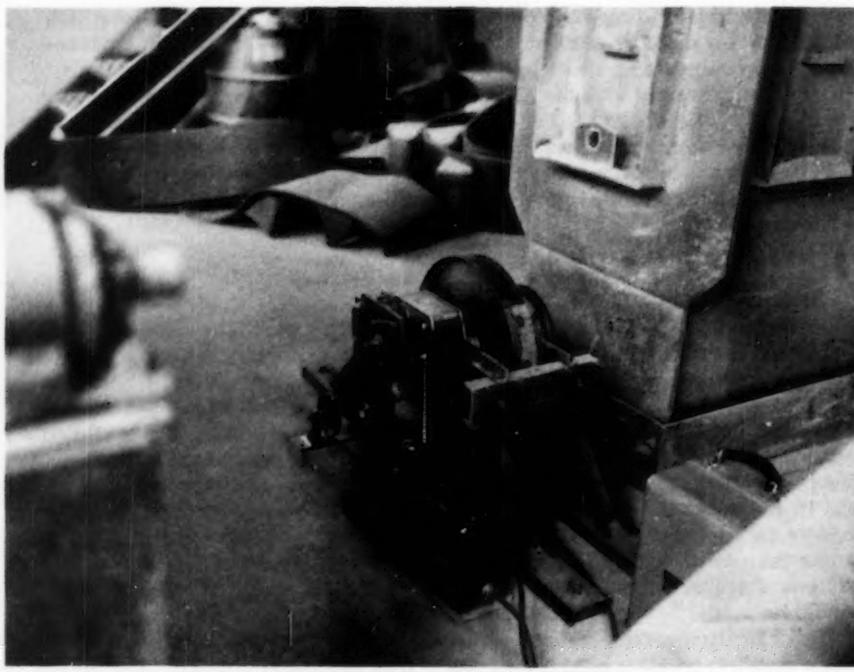


FIG. 12. VIBRATION EXCITER UNIT IN POSITION

adjacent to the upper floor slab accelerometer, as shown in Fig. 4, and was oriented so that the horizontal force was parallel to the short side of the tall portion of the building.

It should be noted that there is a fundamental difference in the behavior of the building when acted upon by the vibration exciter, as compared with its response to the ground motion. Referring to Fig. 13a it will be seen that the ground motion, as discussed above, excites primarily the motion of the two masses in the same direction. The vibration exciter applies a force to just one mass of the system, as in Fig. 13b, and hence tends to excite the motion in which the two masses move in opposite directions. Thus the resonant period excited by the shaking machine will be the shorter period, whereas the period chiefly excited by the ground motion is the longer period. Since the coupling spring between the two masses is very soft compared to the two cantilever springs, for the opposite motion of the masses, the second mass, corresponding to the low portion of the building, can be assumed to have no effect on the system. Thus for the vibration tests the tall portion of the building can be considered as an independent structure.

There is one more difficulty to be encountered before the experimental results can be interpreted. The mechanical exciter unit was considerably smaller than would be desirable for the test, and since the force generated depended upon the rotational speed, for low speeds the force was insufficient to give a measurable motion to the building. This difficulty was avoided by noting that there was a lower period torsional vibration of the floor slab, whose period corresponded to a sufficiently high exciter speed so that usable records could be obtained. Since there is a relatively simple relationship between the period of the torsional vibration and that of the desired lateral vibration, the lateral period could be easily computed.

In Fig. 14 are shown the motions corresponding to the torsional and the lateral vibrations. Considering the floor slab as a uniform rectangular slab of constant thickness, the relation between these torsional and lateral periods is:

$$\text{lateral period} = \sqrt{\frac{12a^2}{4a^2 = b^2}}\ \text{(torsional period)}$$

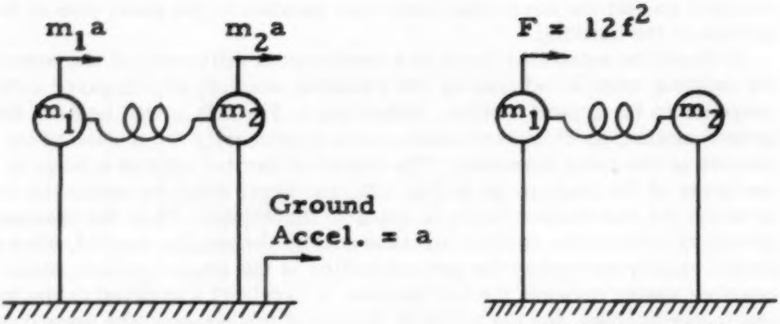
where a and b are defined in Fig. 14.

The same accelerometer and recording system that was used during the blast was used for the vibration test, and the accelerometer was located in the same position. A second accelerometer was mounted at the edge of the floor slab about 25 ft. from the first, and a simultaneous recording of the two accelerometers permitted a distinction between torsional and lateral vibrations. The vibration exciter was located at a sufficient distance from the center of the slab so that torsional motions of the slab could be produced.

The results of the vibration test may be seen in the resonance curve of Fig. 15, where the amplitudes of the building accelerations are plotted versus the exciting frequency (the reciprocal of the period). It will be seen that the resonant period is 1/(5.23) cycles per second = 0.191 seconds. This is the period of the torsional motion, and the desired lateral period can be computed from the expression given above.

$$\text{lateral period} = \sqrt{\frac{(3)\ (65)^2}{(65)^2 + (37)^2}}\ (0.191) = 0.289 \text{ seconds.}$$

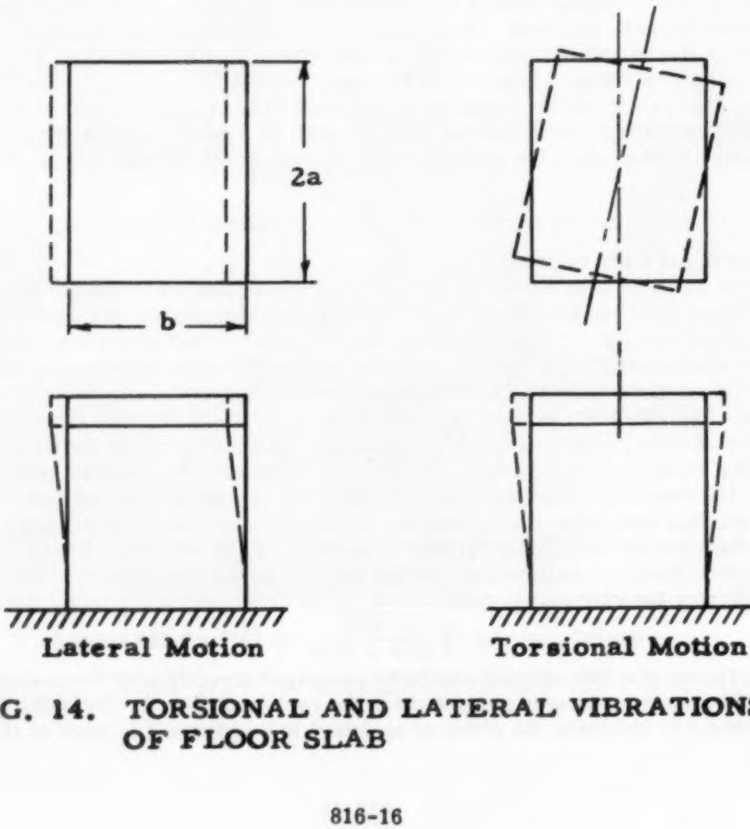
This figure of 0.289 seconds should be compared directly with the period of 0.278 seconds previously computed for the system of Fig. 9. The difference of about 4% indicates the order of accuracy to be expected in work of this kind.



(a) Ground Motion Blast Test

(b) Mechanical Oscillator Test

FIG. 13. COMPARISON OF GROUND MOTION AND EXCITER BUILDING LOADINGS



Lateral Motion

Torsional Motion

FIG. 14. TORSIONAL AND LATERAL VIBRATIONS OF FLOOR SLAB

Determination of Damping

The resonance curve of Fig. 15 is sufficiently well defined so that a value of the equivalent viscous damping can be determined by measuring its width. Since the lower frequencies can be more accurately measured from the record than the higher ones, the rising portion of the resonance curve was used for this determination. If $\Delta\omega$ is the width of the resonance curve at an amplitude $\sqrt{2}/2$ times the resonant amplitude, it can be shown that for small damping, of the magnitude existing in the present test, the fraction of critical damping is approximately $n = (1/2)\frac{\Delta\omega}{\omega}$, where ω is the resonant frequency. For the resonance curve of Fig. 15, this gives a value of n = 0.034.

The dotted curve of Fig. 15 is a computed acceleration resonance curve for a simple spring-mass system, plotted from the equation:

$$\text{acceleration} = \frac{K'\left(\frac{\omega}{\omega_n}\right)^4}{\sqrt{\left[1 - \left(\frac{\omega^2}{\omega_n}\right)\right]^2 + \left[2n\left(\frac{\omega}{\omega_n}\right)\right]^2}}$$

where the two unknown constants K' and ω'_n are determined from the experimentally obtained damping and resonant frequency. It will be seen that the building does behave essentially like a simple system as far as this type of motion is concerned.

The value of equivalent viscous damping obtained in this simplified way is, of course, only an approximate one. The actual damping in the structure is not a viscous type dissipation, and in addition the resonance curve of Fig. 15 does not represent motion in one of the pure normal modes. It is believed, however, that the damping value obtained is useful for comparison with similar tests, and as a basis for an estimation of the energy losses involved in such structural vibrations.

Referring to Fig. 14 it will be seen that the same structural members and the same structural deformations are involved in both the lateral and the torsional motions. The only difference is that in the lateral motion the two end frame structures move together, while in the torsional motion they move in opposite directions. The same value of damping experimentally determined for the torsional motion would thus also apply to the lateral motions.

The low value of damping determined from the present tests (3.4%)shows that large dynamic amplification effects are possible in structures of this type. For this value of damping the maximum dynamic amplification factor at resonance is about 15. This value of 3.4 % damping may be compared with a value of 7 % obtained for a reinforced concrete building, and with values of around 3 % which apply to typical aircraft structures.

Comparison of Transient and Steady State Tests

In comparing the results of the blast and the vibration tests it is well to keep in mind that the amplitudes of the motions in the two tests were quite different, and for some applications this might affect the comparison in a significant way. While accelerations as high as 0.1 g occurred in the blast tests, the maximum accelerations during the vibration tests were of the order of 0.005 g. This difference in acceleration amplitude level could have two distinctly different effects on the results. In the first place the damping in the structure could be considerably greater at the higher amplitudes, and for some positions on the spectrum curve of Fig. 8 this could lead to quite different results. A second effect which might be caused by the large motions

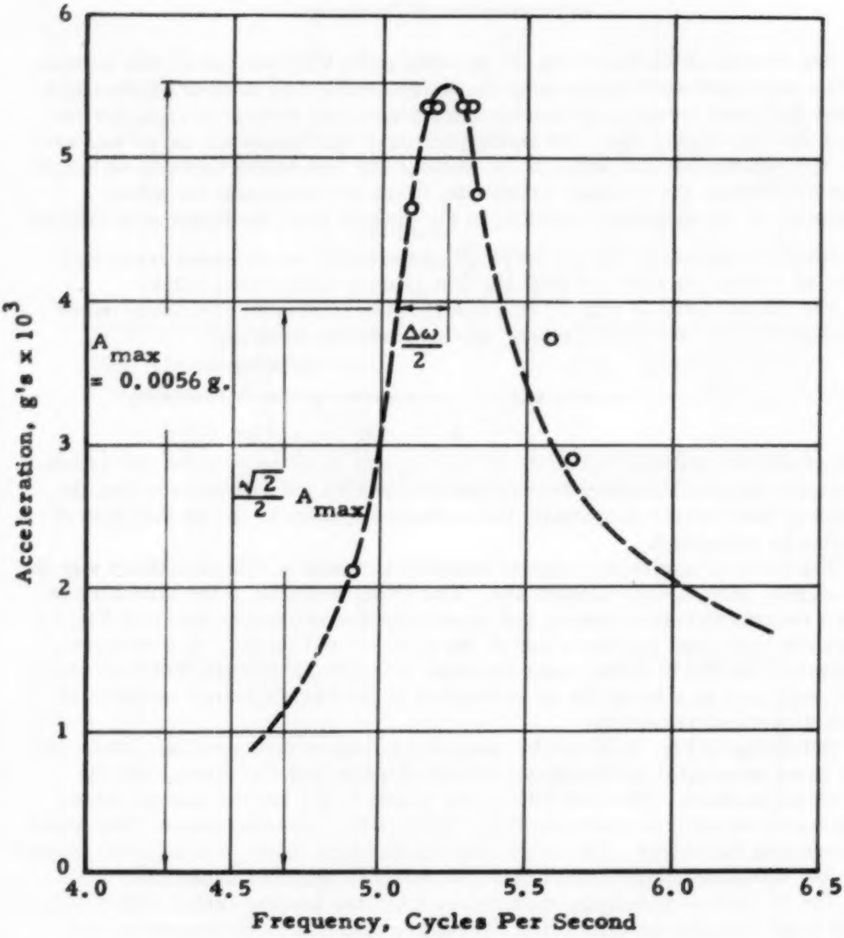


FIG. 15. RESONANCE CURVE OF FLOOR SLAB TORSIONAL MOTION

is the introduction of non-linear effects. If the structure were loaded to the point where some plastic yielding, or buckling of compression members were to occur, then the non-linear character of the restoring force would result in an effective lower natural period, which would alter the behavior of the building. With this thought in mind, calculations were made of the forces acting in the structure, and of the stresses in the compression members. It was found that even under the largest inertia forces of the ground shock motion the axial compression forces did not approach the buckling values, and that no significant structural members were stressed into the plastic region. It was fortunate that for this particular test neither of these amplitude effects operated to change conditions between the large and small amplitudes and hence good agreement was obtained.

One other possible source of difficulty in comparing vibration tests in general with ground motion tests remains to be mentioned. The behavior of

a structure under the action of ground motions may be quite different than that caused by a concentrated exciter force acting at one point. Since many vibration tests have been made on buildings with the idea of determining building response to earthquakes, it is well to emphasize the fact that the earthquake ground motion might excite motions and periods in quite a different way than a force applied at a single point in the structure. This is a problem which has given much trouble in similar vibration tests of aircraft structures where it has been found that in order to properly excite the various wing and fuselage motions, a number of vibration exciters located at various points throughout the structure, and operated simultaneously with the proper phase relationships, are necessary.[7]

CONCLUSIONS

The agreement between the calculated and measured building responses is believed to be well within the limits of accuracy usually required for engineering applications. It thus appears that it may often be possible to replace complex structures by simplified dynamic models that will retain the major features of engineering significance. The difficulties of computing the response of buildings to dynamic loads is a consequence of the complexity of most actual structures and of the exciting forces, rather than to any incompleteness or incorrectness of the dynamical theories applied. The theoretical calculations follow directly from basic physical principles and do not require the inclusion of empirical factors of any kind. Although it is true that judgment must be used in the selection of the best dynamic model to use for the representation of a given complex structure, it is of importance to know that a rational method of analysis exists which can be applied to many structures and which leads to realistic results.

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